Bio Factsheet

Number 35

Structure & Function of the Mammalian Heart

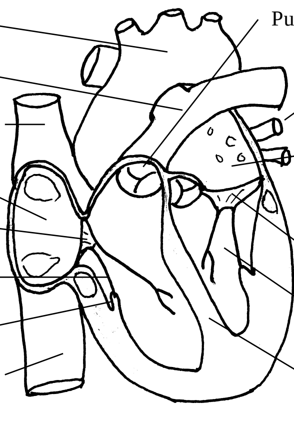
This Factsheet summarises:
1. **The structure of the heart and the histology of cardiac muscle.**
2. **The cardiac cycle and its regulation by the heart itself.**
3. **The modification of the cardiac cycle by nerves and hormones.**

The structure of the heart

The structure of the heart is illustrated in Figs 1a and b. The structure is closely related to its function.

Fig 1a. External structure of the heart, ventral view

Fig 1b. Internal structure of the heart, ventral view



Mammals have a double circulation; the **pulmonary** circulation carries blood to and from the lungs and the **systemic** circulation carries blood to and from the rest of the body. The heart thus acts as a double pump in which the two sides are completely separated by a wall (septum) (Fig 1). The right side pumps **deoxygenated** blood to the lungs for gas exchange with the alveolar air, while the left side pumps **oxygenated** blood to the body for gas exchange with the tissues. The heart has four chambers, the right and left atria and the right and left ventricles. The atria pass blood to the ventricles. The right atrium receives deoxygenated blood from the body via the anterior and posterior venae cavae. This blood is pumped by the right ventricle to the lungs via the pulmonary arch and pulmonary arteries. The left atrium receives oxygenated blood from the lungs via the pulmonary veins. This blood is pumped by the left ventricle to the body via the aortic arch and aorta.

There are valves in the heart and in the veins to maintain a linear flow of blood, i.e. in one direction only. In the bases of the aortic and pulmonary arches are the semilunar valves which prevent backflow from arches to ventricles. Between each atrium and ventricle is an atrioventricular valve which prevents backflow from ventricle to atrium. The tricuspid valve is between the two right chambers and the bicuspid (mitral) valve is between the two left chambers. The atrioventricular valves are held open or closed by tendons (chordae tendinae or heart strings) and are regulated by the papillary muscles of the ventricle wall to which the tendons are attached. It is the slamming shut of the heart valves that results in the typical 'lub-dub' sound that is heard when listening through a stethoscope.

Structure: Function

The walls and septum of the heart are composed of cardiac muscle and their thickness is closely related to the pumping requirement of each chamber (Table 1).

Table 1. Thickness of cardiac walls

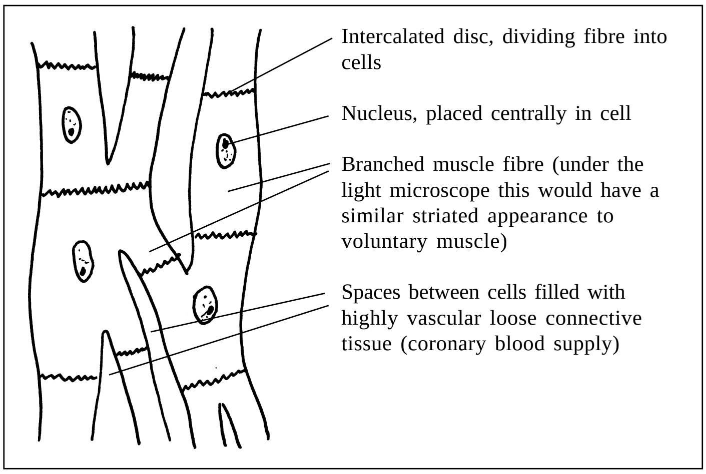
Cardiac Wall	Thickness	Function (reason for thickness)
Atrial walls and atrial septum	Fairly thin	Pumps blood to ventricles = short distance
Right ventricle wall and ventricular septum	Thick	Pumps blood through lungs = medium distance
Left ventricle wall	Extremely thick	Pumps blood throughout body = very long distance

Cardiac muscle has a superb blood supply of its own called the **coronary circulation**. This ensures that the muscle receives adequate nutrients and oxygen for its continual functioning and that waste products are removed efficiently. The human heart beats on average 72 times every minute throughout life and so the coronary circulation has to be super-efficient. The cardiac muscle is arranged as a 'basin shaped' mass of tissue around each heart chamber, and so contraction of its cells results in a decreased chamber volume thus forcing blood onwards.

The histology of cardiac muscle

This is illustrated in Fig 2 overleaf. The contractile proteins of cardiac muscle are arranged into sarcomeres, fibrils and fibres as in voluntary striated muscle, but in cardiac muscle the fibres are arranged into branched, short individual cells with elaborate junctions (intercalated discs) between them. These discs are highly folded interlocking areas of the cell membrane (sarcolemma) consisting of areas of adhesion to hold the cells together in a sheet formation, and of areas where rapid ion transport can occur from cell to cell, thus allowing waves of depolarisation (contraction) and repolarisation (relaxation) to pass through the tissue. Between the cells are numerous capillaries of the coronary circulation. Within the cells are many mitochondria

Fig 2. Histology of cardiac muscle tissue. Light microscopic features



enabling the tissue to have a very high metabolic rate for long periods, when needed. The tissue is said to be **'myogenic'** which means that it will contract and relax rhythmically of its own accord throughout life. The nervous system is only involved in altering the frequency and force of these contractions to meet body needs.

The sheets of cardiac muscle making up the walls of the heart are firmly anchored to a tough ring of collagen fibres which makes up the skeleton of the heart. This is situated in the wall of the heart between the atria and the ventricles, and runs round the full circumference of the heart in this region.

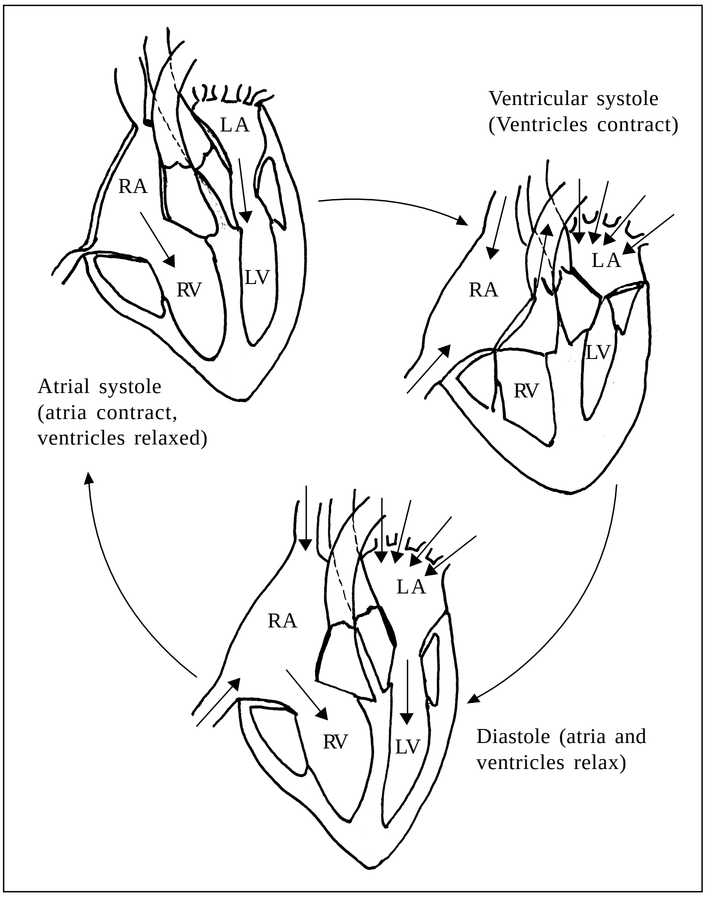
The cardiac cycle

The pumping activity of the heart is described as the cardiac cycle. One cardiac cycle consists of systole (contraction) and diastole (relaxation). The two ventricles contract simultaneously from the apex upwards but the atria contract a fraction of a second before the ventricles, the right atrium contracting slightly before the left atrium. This sequencing of contractions, coupled with the actions of the valves, ensures a linear flow of blood which would not occur if all parts of the heart contracted and relaxed simultaneously. As long as the heart is pumping effectively there should be no damming up of blood, and the cardiac output from the ventricles should equal the venous return to the atria. The stages of the cardiac cycle are as follows:

1. Initially the heart is in diastole with atria and ventricles relaxed, the atrioventricular valves are open, but the arch semilunar valves are shut.
2. The venous return of deoxygenated blood from the body enters the relaxing right atrium through the venae cavae.
3. The venous return of oxygenated blood from the lungs enters the relaxing left atrium through the pulmonary veins. At this stage some blood also passes through the open atrioventricular valves into the relaxing ventricles.
4. When the atria are full, their walls contract (**atrial systole**) pushing blood through the open atrioventricular valves into the relaxed ventricles. Blood cannot pass back into the veins because they contain valves which prevent backflow, and also the contracting of the atrial walls partly closes off the entries of the venae cavae and pulmonary veins to the atria.
5. After a short delay the ventricles contract from the apex upwards, forcing the blood at high pressure into the arches. At this time the atrioventricular valves slam shut, preventing backflow of blood to the atria, and the arch semilunar valves open to allow the passage of blood into the arches.
6. When the ventricles relax (**diastole**) the sudden fall in pressure causes the arch semilunar valves to slam shut, thus preventing backflow of blood from the arches.

Fig 3 illustrates the cardiac cycle.

Fig 3. The heart at different stages of the cardiac cycle



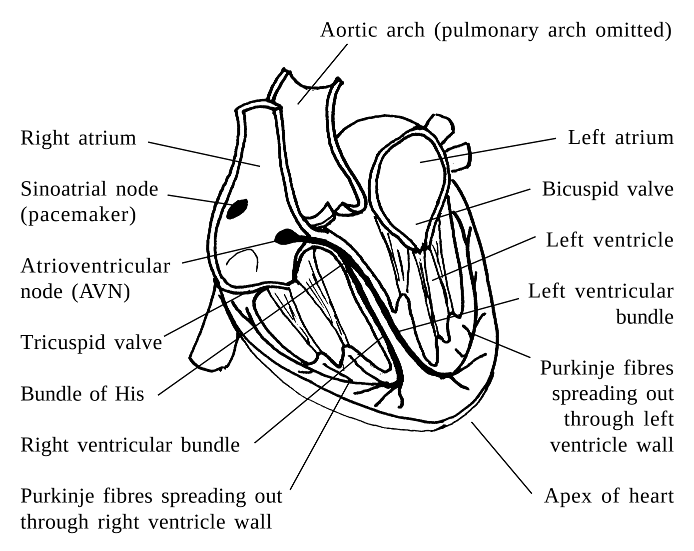
The **cardiac output** is the volume of blood pumped out by the heart in dm^3 per minute. In humans, at rest, this averages around 5 $dm^3\ min^{-1}$ and can rise to around 20$dm^3\ min^{-1}$ during severe exercise. The 'stroke volume' of the heart is the volume of blood forced out per beat, and can be calculated by dividing the cardiac output by the beat frequency per minute. For instance, at rest, with a cardiac output of 5 $dm^3\ min^{-1}$ and a beat frequency of 70 beats per minute, the stroke volume would work out to a value of 71.4 cm^3 per beat.

Regulation of the cardiac cycle by the heart itself

Owing to the myogenic nature of cardiac muscle, the heart beats of its own accord in a co-ordinated sequential pattern, even if the nervous connections to the heart are severed, for instance, in transplant surgery. Due to ion exchange across the intercalated discs, the contraction of one cell will stimulate the contraction of other cells at either end. Thus, the cell with the fastest rate of spontaneous contraction will impose its rate on the surrounding cells.

The region of the heart that has the highest inherent rhythm is called the **sino-atrial node (SAN or pacemaker)** which is situated in the wall of the right atrium between the entries of the superior and inferior venae cavae. This node initiates waves of depolarisation (which cause contraction) which spread first through the wall of the right atrium and then through the wall of the left atrium. This is why the right atrium always contracts slightly before the left atrium. The waves of depolarisation cannot pass through the heart wall from atria to ventricles because of the high electrical resistance of the ring of collagen making up the heart skeleton, but can only pass via a region of conducting tissue, called the **atrioventricular node (AVN)**, which is situated at the top of the ventricular septum (Fig 4)

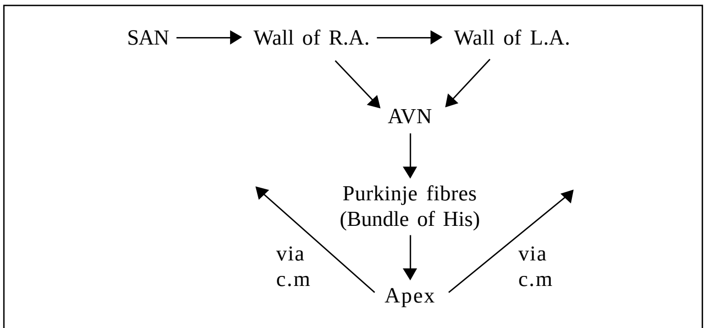
Fig 4. Internal view of heart to show the conducting system



From here the depolarisation impulses are passed rapidly to the apex of the heart through specialised conducting cells, called **Purkinje fibres** (sometimes spelt Purkyne). These fibres make up the left and right ventricular bundles, which together are called the **Bundle of His**. From the apex, the waves of depolarisation pass through the cardiac muscle fibres of the ventricles, therefore causing contraction to occur from apex upwards.

When the impulses pass through the atrioventricular node, they are delayed for about 1/10th of a second. This ensures that ventricular contraction occurs after atrial contraction. As the cardiac muscles repolarise back to the resting state, they will relax. The nodes, bundle of His and Purkinje fibres make up the conducting system of the heart. The above processes are summarised in Fig 5.

Fig 5. Nervous stimulation of the heart



Modification of the cardiac cycle

1. **By hormones**
   Adrenaline and **noradrenaline**, produced by the adrenal medulla, increase the rate and force of cardiac muscle contractions, and also bring about dilation of the coronary arterioles thus improving the blood supply to the heart muscle. The actions of these hormones is counteracted by the actions of **acetylcholine** from the parasympathetic system (PNS).

2. **By the nervous system**
   Although the cardiac cycle is initiated and co-ordinated by the heart itself, the cardiac output must be adjusted to meet the varying needs of the body, and this involves the use of sensory receptors and the autonomic nervous system. Stimulation of the heart by the sympathetic nervous system (SNS) increases cardiac output, by:
   (i) increasing the frequency of the heartbeat, and
   (ii) increasing the force with which the cardiac muscle contracts.

Stimulation of the heart by the parasympathetic nervous system reduces the cardiac output by reducing the beat frequency and force of contraction.

These two systems operate through **negative feedback control** involving two controlling centres in the medulla of the brain. These are the **cardioacceleratory centre** (CAC) which is concerned with increasing cardiac output and the **cardioinhibitory centre** (CIC) which reduces cardiac output.

From the CAC, sympathetic nerves pass down the spinal cord and exit as accelerator nerves to the sinotrial node, atrioventricular node and cardiac muscle fibres, where they release **noradrenaline**. This stimulates the sinoatrial node to increase its depolarisation frequency, reduces the delay at the atrioventricular node and increases the force of the muscular contractions. Thus the cardiac output rises.

From the CIC, parasympathetic fibres pass through the vagus (10th cranial) nerves to the sinotrial node and the atrioventricular node, where they release **acetylcholine**. This suppresses the activity of the sinoatrial node and increases the delay at the atrioventricular node. Thus the cardiac output falls (Table 2).

Table 2. SNS and PNS control of cardiac output

System	Transmitter	Effect
SNS	noradrenaline	↑ heart rate & force, ↑ cardiac output
PNS	acetylcholine	↓ heart rate & force, ↓ cardiac output

Stimulation or inhibition of the cardiac control centres involves three separate reflex pathways which are associated with blood pressure receptors (**baroreceptors**) situated in different positions.

The reflexes are:
- the carotid sinus reflex
- the aortic reflex
- the Bainbridge reflex.

The carotid sinus reflex is concerned with maintaining the correct blood supply to the brain. The carotid sinus is a swelling on the base of the internal carotid artery to the brain and the baroreceptors are in its wall. If the blood pressure rises the sinus wall is stretched and the baroreceptors fire off impulses to the cardioinhibitory centre, thus cardiac output is reduced and blood pressure falls. As the sinus wall becomes less stretched, the baroreceptors are no longer stimulated and the cardioacceloratory centre now dominates, thus raising cardiac output and blood pressure.

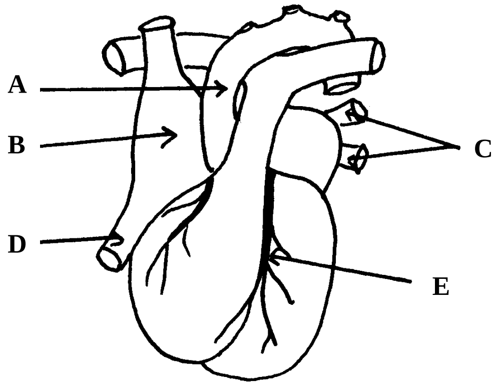
The aortic reflex is concerned with maintaining the correct blood pressure in the aorta and general circulation. Aortic bodies in the wall of the aortic arch contain the baroreceptors. The aortic reflex operates basically in the same way as the carotid sinus reflex.

The Bainbridge reflex regulates venous pressure. Baroreceptors in the walls of the venae cavae and right atrium fire of impulses to the cardio acceleratory centre thus increasing cardiac output and thus increasing venous return and venous blood pressure.

Exam Hint *- Candidates are very rarely asked to draw the heart. Labelling the structure and identifying the nervous pathway of the cardiac cycle is much more commonly asked. When revising, condense the cardiac cycle, the nervous pathways and the action of the SNS and PNS into a flow chart.*

Practice Questions

1. The diagram below shows the external appearance of a human heart.



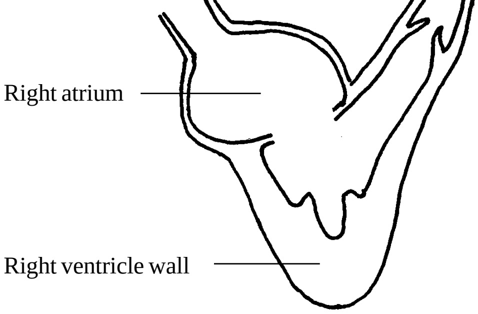
(a) Identify structures labelled A, B, C and D
A .... B..
C.. D..
(4 marks)

(b) State the functions of the part labelled E.
(2 marks)

(c) The following pressures occur in the heart during a complete cardiac cycle, 0 mm Hg, 20 mm Hg and 180 mm Hg.
Which of these pressures do you think is associated with:
Atrial systole ....
Ventricular systole ....
Diastole .... (3 marks)

2. Read through all of the following passage and then fill in the spaces with the most appropriate word or words.
The cardiac cycle is initiated and controlled by the heart itself. Cardiac muscle is said to be .... since it will contract and relax of its own accord. The beat is initiated by the ....which is situated in the wall of the .... Waves of depolarisation travel through the atria causing atrial .... The waves of depolarisation can only travel to the ventricles via the .... situated at the top of the ventricular septum. From here the waves travel to the apex of the heart through the .... which is made of specialised conducting cells called .... These then carry the waves of depolarisation through the ventricle walls causing both ventricles to contract simultaneously. At this stage the .... are open and the .... are shut so that blood can be forced into the arches.
(9 marks)

3. The diagram below shows the right side of the heart during ventricular systole.

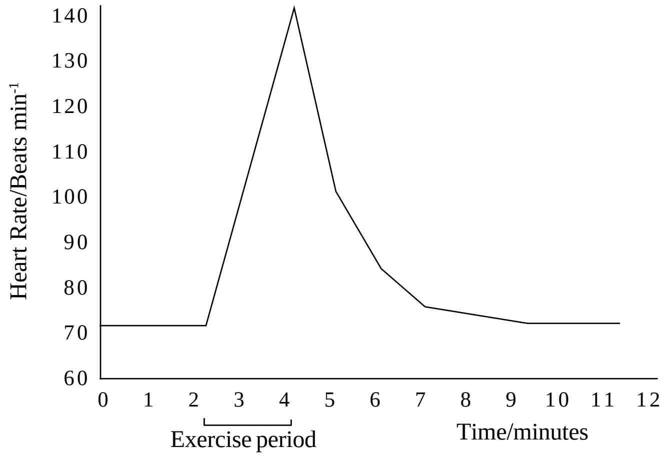


(a) Draw on the diagram the position of the valve and valve tendons between the right atrium and right ventricle while the ventricle is contracting. (2 marks)

(b) What would happen if the valve was not in the correct position?
(1 mark)

(c) (i) Which organs does the blood go to on leaving the right ventricle?
(1 mark)
(ii) What changes occur in the blood when it reaches these organs?
(3 marks)

4. The heart beat rate of a student was measured before and after a period of 2 minutes exercise. Immediately before and after the exercise the student rested in an arm chair. The results are presented in the graph below.



(a) (i) By how many beats per minute did the heart rate increase during the exercise period? (1 mark)

(ii) How long did it take after the exercise for the heart rate to return back to the resting level? (1 mark)

(b) (i) Describe the physiological mechanisms involved which caused the increase in heart rate during the exercise.
(ii) Explain why the return to the resting rate was only gradual.
(2 marks)

5. For each of the following features associated with the cardiac cycle, describe its location, and state one of its functions.

Feature	Location	Function
Carotid body (sinus)		
Cardio acceleratory centre		
Purkinje tissue		
Coronary capillaries		
Papillary muscles		

(10 marks)

Answers

Semicolons indicate marking points

1. (a) A = aortic arch;
   B = right atrium;
   C = pulmonary veins;
   D = inferior/posterior vena cava;

   (b) Coronary arteries/veins to carry blood to and from cardiac muscle;
   Provides very efficient oxygen supply to cardiac muscle/very efficient removal of carbon dioxide;
   Enabling efficient working/respiration of heart muscle;

   (c) Atrial systole 20 mm Hg;
   Ventricular systole 180 mm Hg;
   Diastole 0 mm Hg;

2. myogenic;
   sinoatrial node/pacemaker;
   right atrium;
   systole/contraction;
   atrioventricular node;
   bundle of His/left + right bundle branches;
   Purkinje fibres;
   semilunar valves;
   atrioventricular valves;

3. (a) Valve flaps closed;
   tendons from valve flaps to papillary muscles;

   (b) If the valve was not closed then the systole blood would be forced back to the atrium rather than to the lungs for oxygenation;

   (c) (i) Lungs;
   (ii) Offloads CO_2;
   thus blood hydrogen carbonate concentration falls;
   onloads O_2;
   reformation of oxyhaemoglobin;

4. (a) (i) 70 beats per minute;
   (ii) 5 minutes;

   (b) (i) Increased respiration leads to a decrease in blood O_2 tension/increase in blood CO_2/HCO_2 tension;
   sensed by chemoreceptors in aortic/carotid bodies;
   impulses sent to CAC centre in medulla;
   this increases sympathetic stimulation of the heart;
   this increases frequency of depolarisation of the sinoatrial node which increases heart beat rate;
   CIC inhibited so parasympathetic stimulation of heart reduced during this time;

   (ii) Blood O_2/CO_2/HCO_3 tensions take time to be returned to resting levels;
   by ventilation mechanisms/breathing;
   thus CAC not suppressed for several minutes;

5.

Feature	Location	Function
Carotid body (sinus)	Base of internal carotid arteries;	Senses blood pressure/O_2/CO_2 tensions;
Cardio acceleratory centre	Medulla (oblongata);	Increases cardiac output;
Purkinje tissue	Bundle of His/between cardiac muscle fibres in ventricles;	Rapid transmission of impulses to ventricular muscle;
Coronary capillaries	Between cardiac muscle fibres;	Provide good blood/O_2/glucose supply to muscle/efficient CO_2 removal;
Papillary muscles	On inside of ventricle walls;	Regulate AV valve opening and closing;

Acknowledgements;
This Factsheet was researched and written by Martin Griffin
Curriculum Press, Unit 305B, The Big Peg,
120 Vyse Street, Birmingham. B18 6NF

ISSN 1351-5136